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ACCOMPLISHMENTS IN HUMAN OPERATOR SIMULATION

67/100

by

G.E. Briggs and *R.L. Cosgriff*

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THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION
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REPORT

by

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ABSTRACT

A brief review of events leading up to the development of the transfer function techniques is made with special reference to use of the techniques to explain human behavior in continuous control tasks. Consideration is then given to recent research on the development of nonlinear transfer functions and to the applications made by engineers and psychologists in designing control tasks for the human operator.

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ACCOMPLISHMENTS IN HUMAN OPERATOR SIMULATION

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G. E. Briggs* and R. L. Cosgriff**

PREFACE

This report was prepared initially as a paper for presentation at the 1960 Summer Annual Meeting and Aviation Conference of the American Society of Mechanical Engineers. It is in essence a tutorial and historical approach to those events culminating in the present research on man-machine control systems, and, as such, is not a direct result of this research, but a corallary and independent study. The broad scope of this paper and its pertinence to more specific studies of man-machine problems makes it of obvious interest to researchers in this problem area; the report form, therefore, has been adopted as an efficient means of making the information readily available to those most highly concerned with work of this nature.

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INTRODUCTION

From earliest recorded history we find that man has been understandably curious about himself. He has long sought the reasons behind his behavior, the "how" and "why" of performance. Down through recorded history one can note a succession of guesses made by learned men as to the inner workings of man. Throughout all of these hypotheses runs a common thread: in each theory of human behavior some form of inner activity has been assumed to account for the reason man behaves as he does. Thus, the very primitive culture hypothesized that there existed inside of every human body another man. This man within the man or spirit within the body determined and guided the responses of the human body. Later the Greek philosophers, including Plato and Aristotle, developed more sophisticated hypotheses regarding the "inner self" and called this inner determinate the "mind." The mind was conceived to be nonmaterial in form—without physical form. It was not a physical man within a physical man, but rather impressions or "ideas," as Aristotle termed it, which resulted from man's experience with his environment. These lasting impressions permitted man to "reason" and thus controlled the behavior of man in his interaction with his environment.

These views of the determinants of man's behavior received a major overhaul during the Rennaissance when philosophy began to flower again. Descartes in particular proposed that man can and does behave in a mechanical manner. Further, these mechanical processes were said to be triggered off by external energy sources such as light patterns and sounds. To Descartes, then, man was in part a machine capable of being understood by reference to machine analogs.

In the three hundred years since Descartes's death theories of human behavior have undergone many changes—one can see these theories as running a course much like that of a pendulum swinging far over in one direction at which point man's behavior was thought to be quite nonmechanical in nature—in fact it was most important in the Victorian age to assume that man was more than a mere animal and much more than a mere machine; indeed, the concept of a mind was changed during this period to the concept of a soul within the human body, and the concept of the soul included overtones of devine guidance to behavior. Today, the view is swinging back to Descartes' type of thinking. There are three major reasons for this increasing emphasis on understanding man by reference to machine analogs. One reason is the tremendous strides made in the biological sciences, the second is the relentless pressure for automation and the significant breakthroughs made by mathematicians and engineers in this area, and the third is the result of comprehensive empirical research conducted by psychologists over the past eighty years on human performance in a variety of information-processing tasks. Let us consider these reasons in brief detail.

First, in the biological sciences and in physiology in particular, we find that information on the central nervous system has increased in an ever accelerating manner. We understand today much about the major neural passages linking the peripheral sense organs, such as the eye, the ear, and the proprioceptive mechanisms of the arms and legs, to the brain. Further, we have rather detailed information on the division of functions between the several parts of the brain. Finally, we have considerable information on the major neural passages linking the brain to the appendages—the arms, hands, fingers, legs, and feet. We know, in other words, a great deal (but not all, by any means) about the neural system and the way it provides a basis for the control of behavior. For example, we understand fairly well the kind of coding activities carried on by the peripheral sense organs such as the eye. We know also that extirpation of certain areas of the brain will cause exaggerated movements of the limbs, thereby suggesting that suppressor mechanisms represent part of the functions of the brain. We know that the thalamus, a part of the lower or more primitive brain, is a complex relay station. We know that at the highest brain level, the cerebral cortex, there are localized areas devoted to specific functions such as hearing, seeing, speech, limit movements, etc., and that several such areas interact extensively to determine man's variable response to his environment. These interactions may be assumed to provide the basis for most of the so-called higher-order mental processes such as thinking, reasoning, and problem solving.

Thus, the empirical facts of neurophysiology have provided us with rather extensive knowledge on neural passageways and neural mechanisms. In some cases we can account for aspects of human behavior by direct reference to neural mechanisms, but in many cases one must still hypothesize that the neural system carries out certain functions. In many ways, therefore, we are in the same position as Plato, Aristotle, and Descartes—we must still make educated guesses as to the "how" and "why" of human behavior. In other words, we must rely on theory and conceptual models to explain much of man's complex behavior, since with our present knowledge of the nervous system we are rather limited in the direct references we can make from observable behavior to known neural mechanisms and processes.

In order to show how physics and engineering have contributed to theory and conceptual models of human behavior, let us consider briefly the major events that have occurred in automation and control. The earliest work of importance is that of JamesWatt who not only demonstrated that the energy of fossile fuels could be employed to replace the brawn of man but also invented one of the earliest control systems, the flyball regulator. The modern control did not immediately develop after Watt's work for several reasons. First it was necessary for the concepts of communications and feedback to be conceived; it was necessary for mathematical techniques to be developed; it was necessary for components to be available for these systems. Thus Babbit's mathematical machine, Morse's telegraph, the operational calculus of Heaveside. The work of the "Giants" at Bell Laboratory during the twenties and the development of electronics provided the foundation for the modern control field. Thus, the control field expanded rapidly after Minorsky's work in the 1920's and Hazen's introduction of the servomechanism in the early thirties.

Psychology has existed as a field of inquiry independent of its parent field, philosophy, for approximately eighty years. In these eight decades we have seen significant strides made in describing and measuring human abilities and characteristics such as intelligence, interests, aptitudes, etc. We can see also that much has been learned through both field and laboratory research of the bases for human behavior under the topic headings of learning, motivation, perception, etc. It is interesting to note that much of this work has been carried out under a variety of theoretical orientations and, as such, it may be viewed as a mosaic of empirical data with only vaguely apparent unity. The basic problem appears to be the lack of a conceptual model for human behavior which would exert a unifying influence on both the design of individual research studies and the interpretation of empirical data.

Today, the picture has changed dramatically. Thanks to the recent appearance of modern communication theory and to the development of feedback control theory, psychologists now have that essential requirement for significant advances in our understanding of the internal processes we have been calling perception: we have specific conceptual models by which it is possible to collect the bits and pieces of empirical information on perceptual processes into a meaningful interpretation of human behavior in complex control tasks.

TRANSFER FUNCTIONS FOR THE HUMAN OPERATOR

By reference to communication theory and feedback control theory the psychologist finds it possible to show consistent relationships between human behavior in such common activities as walking, talking, and manipulatory acts involved in writing, telegraphy, playing musical instruments, typewriting, and the like. Human behavior in these tasks can be viewed as occurring in a closed-loop system with the input from man's environment being first recoded at the sensory receptors such as the eye, and secondly undergoing learned transformations (perceptual responses) which in turn activate particular muscular responses. The results of these overt movements are fed back to the internal control mechanisms via both visual and proprioceptive sense modalities to close the loop and provide a basis for the elegant patterns of response one observes in the highly skilled operator.

By reference to control theory one is able also to make consistent interpretations of human behavior in a wide variety of situations requiring human control of complex processes such as steering a car, flying an aircraft and controlling depth in a submarine. Thus, one is not misled in interpreting the behavior of a child steering a tricycle as being qualitatively different from the behavior of the interceptor pilot steering his aircraft on a collision course with a target; rather one sees that the controlling responses differ quantitatively not qualitatively and that the major difference between behavior in these two skill tasks is in the level of complexity of the information processing required: the pilot is in control of a machine with far more complex dynamics than the child's tricycle and this requires more complex perceptual processing. Thus, since the pilot is dealing with more complex dynamics, his perceptual response must include estimates of higher derivatives of the input signals than in the case of the child.

It can be seen, therefore, that the servo model provides a unifying frame of reference for our understanding of human behavior in a variety of skill tasks. But the servo model does far more for the psychologist than this. It provides a machine analogy from which it is possible not only to infer specific perceptual processes but to quantify the weights attached to these processes by the human operator. Let us explore these points in some detail.

One way to interpret a transfer function which has been fitted to controlling responses of a human operator is to say that the equation represents those translations and transformations which if they had been applied to the known input signals would have resulted in outputs similar to the measured response of the human operator. For example, let us consider one of the earliest derivations of a human transfer function—that provided by Tustin in 1947 (1).* Tustin fitted the following differential equation to some data recorded from human controlling behavior in a task involving machine dynamics:

$$py = (K_1x + K_2px)\, e^{-Tp} \qquad \text{Equation (1)}$$

where py represents rate of change in limb movements, x is the instantaneous magnitude of system error, px is the rate of change of error, K_1 and K_2 are gain

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* Numbers in parentheses refer to similarly numbered references in bibliography at end of paper.

constants, and e^{-Tp} represents an exponential time lag analogous to human reaction time and was intended to account for the lag of the operator in tracking continuous inputs.

Upon fitting the above equation to tracking data, Tustin found a best fit when he added a constant bias to the left-hand term. The result was as follows:

$$(.11 + p)y = x\ 22(1 + 2.3p)\ e^{-.3p} \qquad \text{Equation (2)}$$

It is apparent that Tustin's transfer function assumes that the human operator responds not only to the instantaneous magnitude of system error but to the first derivative of that signal as well. Indeed, it is of particular significance to a psychologist that Tustin's human tracker attached considerably more weight to the first derivative of error than he did to error magnitude, i.e., K_2 was 2.3 times greater than K_1.

Since Tustin's equation provided a rather good fit to the data we may infer that the human operator probably did carry out some form of information processing which was related both to error magnitude and to error rate. This is significant to the psychologist since it provides a strong clue to the kinds of information-processing activities required of the human in complex control tasks—activities analogous to amplification and differentiation. Of particular importance to the psychologist is the fact that the technique of deriving human transfer functions not only provides indications of the kind of operations probably carried out by internal human mechanisms but also a fit of the equation provides an indication of the relative weights the human assigned to these several perceptual responses.

Thus, engineering has provided the psychologist with a powerful tool by which it is possible not only to specify perceptual processes in detail but also to quantify these internal activities. We cannot stress too highly the significance of this advance in methodology. Now, the human transfer function methodology has undergone and continues to undergo improvements. It became apparent quite early that the linear differential equation, as used by Tustin and others, does not fit data from the human controller as well as might be desired since the human brings many nonlinearities to the control task. Thus, the later efforts of personnel at Ohio State, at MIT, at the Goodyear Laboratories, and at The Franklin Institute have included nonlinear characteristics in the derived transfer functions. The attempt, of course, has been to reduce the nonlinear remanent in such functions.

Control Aspects of Tustin's Representation

Let us consider the nature of such recent work by a further analysis of Tustin's contribution (1). Tustin suggested that the response y of a human operator could be represented by two terms, namely G(p)x, where x is the stimulus and G(p) is a linear transfer function, and a second additive correction term or remanent term y_r; thus

$$y = G(p)x + y_r \qquad \text{Equation (3)}$$

The RMS value of y_r can be shown to be a minimum if G(p) is chosen such that there is no correlation between y_r and x.

One of the major questions then arising is whether y_r is deterministic or probablistic in nature. If the process is nonlinear in nature it is likely that a portion of y_r is deterministic in nature. It appears reasonable from gross static considerations of the human operator that certain nonlinear effects are certainly present. Considering what is known today about the sensory elements, the brain, the nervous system, and the motor system of the human body, it is also apparent that each such process is far from linear. In fact, it is rather surprising that G(p)x accounts for as large a portion of y as it does. Certainly, then, one can say that part of y_r is deterministic as has been shown by the Goodyear and OSU simulation of the human operator (2, 3).

Therefore, y can be represented by

$$y = G(p)x + y_{rd} + y_{rp} \qquad \text{Equation (4)}$$

where y_{rd} is the deterministic portion of y_r and y_{rp} the probabalistic portion. The portion of y that is predictable, namely $G(p)x$ and y_{rd}, is exactly the representation used by Booton (4) in his representation of a nonlinear filter, and presumably from these two terms one could synthesize a nonlinear filter which would duplicate $G(p)x + y_{rd}$. At first glance one would think that one could reasonably simulate the human operator by means of the nonlinear filter and a suitable noise source. Yet this step is rather dangerous in that we know from experience that once the nature of x is altered the human operator will change, thereby causing a change in $G(p)$. The nonlinear filter would also indicate a change of $G(p)$; however, the human will arrive at a new value of $G(p)$ relatively slowly during which time the RMS value of y_r will slowly diminish. On the other hand, Booton's filter would achieve a stationary $G(p)$ in a relatively short transition period. Therefore, the nonlinear filter approach is valid only when the operator has passed through a learning period and during periods where both the environment of the controlled system and the statistical parameters of the signal x are stationary. It can be concluded that the nonlinear filter considerations cannot be used to completely analogue the active perceptual processes employed by the operator during the learning stages.

The nature of $G(p)$ and therefore the remanent term of y is a function of two major aspects of the task. First, there is the matter of the informational content of x. If it is low, the operator will tend to improve his performance.

The second factor is associated with the bandwidth of the spectrum of x. Generally, the lower this spectrum the better the human response will be. G(p) can become quite refined, and the smaller will be the remanent term.

Returning to the human operator, we find that his response to signal components in the upper frequency range, above one cps, tends to become erratic. It is therefore not surprising to learn that the spectrum of y_d will be relatively small in the low frequency range and concentrated to some extent in the upper frequency range. For this reason the upper frequency characteristics of G(p) are relatively unimportant, providing G(p) provides the necessary attenuation in this range, while the lower frequency characteristics of $G(j\omega)$ are of first importance.

The usual proposed transfer function G(p) is of the form

$$G(p) = \frac{K(e^{-\tau_o p})(p\tau_1 + 1)}{(p\tau_a + 1)(p\tau_b + 1)} \qquad \text{Equation (5)}$$

where the transport lag τ_o, and the remaining time constants are chosen to provide an optimum fit to G(p) in the low frequency range and attenuation in the upper frequency range. This selection of the transfer function is based upon both intuition and convenience. Thus τ_o is chosen on the basis of the time lag encountered in the brain and nervous system in the transmission of information while τ_b is chosen on the basis of the muscular response characteristics.

Probably the most accurate simulation of the human operator was that accomplished by the investigators at Goodyear Aircraft (2, 3). The simulator diagram is shown in Fig. 1.

The operator controlled a simulated aircraft as shown in Fig. 2. The nonlinear terms introduced in the Goodyear simulator accounted for a large portion of the remanent terms indicating that the remanent terms are of a deterministic nature. The simulation could probably have been improved by adding a saturation factor to the dead zone element as indicated by the dotted lines of Fig. 2.

OSU SIMULATION

The OSU group is interested in observing the nature of G(p) during the learning phases of the human and for this reason the transfer function G(p) is automatically synthesized by means of an analogue computer. The simulator is excited by the same stimulus as that observed by the human operator (see Fig. 2). The difference ϵ between the operator stick position and the output signal generated by the simulator is determined. One section of the computer excited by this difference signal then adjusts the simulator so as to keep it in step with operator characteristics (for general characteristics of this system see Reference 7). This procedure allows one to quickly determine transfer characteristics which are so difficult and time consuming to determine using the mathematical correlation techniques. It is hoped that the information gained from this study will give an insight into the nature of the human operator and particularly the adaptive nature of the human operator. Typical operator and simulator characteristics are shown in Fig. 3.

CONTROL THEORY AND THE DESIGN OF MAN-MACHINE SYSTEMS

It is seen, from the above, that the recent developments in control theory have provided psychologists with excellent models for the making of inferences as to the internal perceptual processing functions of the human operator. It will be of interest to note that the psychologist has been quick to capitalize on these advances at both theoretical and applied levels. Let us conclude this paper with a brief review of the recent applications of control theory made by psychologists.

One of the major benefits which has derived from control theory is that one can describe the man and the machine in a common language. In other words, control theory makes it possible to treat man as a link in a control system and to describe his assigned control functions in the same language as that used to describe the machine portions of the system. This common language has facilitated the design of man-machine systems which design takes advantage of the capacities of the human operator and compensates for his known deficiencies.

To illustrate this latter point, let us consider a now classic report published by a psychologist and an engineer at the Naval Research Laboratory in 1954 (5). These men, Franklin V. Taylor and Henry P. Birmingham, noted that the human operator does a rather poor job of differentiating input signals, but that he is a good amplifier. Thus, if we placed a human operator in a system such as that shown in Fig. 4, we can expect him to do only a fair to middling job since the presence of integral dynamics in the machine requires the human to estimate the first and second derivatives of the error signal in order to stabilize the system.

Birmingham and Taylor proposed what is now called the <u>quickening principle</u> which relieves the human of performing functions analogous to differentiation. With quickening, the feedback loop contains not only the system output but its first and second derivatives as well, as shown in Fig. 5. These "derivative" signals are weighted by appropriate gain adjustments and the task required of the human reduces to that of a simple amplifier. The quickening principle has been applied to such difficult tasks as submarine depth control and helicopter hovering control. The increase in accuracy of control has been astounding.

It is of interest to note that the quickening principle achieves much the same result as that obtained by an earlier technique called "aided laying" or simply, aiding. In aiding, the engineer provides a feedforward loop around the integral transformations such as those shown in Fig. 6. Thus, if the gains on these feedforward loops are set at appropriate levels a movement of the operator's control device calculated by him to correct a perceived amplitude of error will also correct error rates and accelerations as well. Since the human needs to respond to the amplitude of error, his task is that of a simple amplifier, as in the quickened system. It should be noted, however, that aiding and quickening are different in that the former affects the output signal directly while quickening affects only the feedback signal. In most cases the integral transformations shown in Fig. 4 represent the dynamic interaction of a vehicle with its environment and so aiding cannot be applied to the system—quickening the system can be accomplished since, as indicated, this operation affects only the feedback loop.

Another form of aiding is of interest here—that called display aiding. This operation is shown in Fig. 7 as the insertion of a phase advance network just prior to the information display. Since the system shown in Fig. 7 also has been quickened, we would designate the system as one involving quickening plus display aiding. Let us see what this does for the human operator. It may be recalled that the presence of a quickened feedback signal means that the task of the human operator is analogous to that of a simple amplifier. Thus, the human information-processing task involves simply relating the amplitude and direction of system error to the positioning of the control device. Now, if we add display aiding to a quickened system, we further reduce the complexity of human information processing in that the human needs to consider only the direction of system error and he can disregard its amplitude. Thus, if the system has been subjected to quickening, the human must perform a perceptual operation analogous to that of a simple amplifier while if the system has been subjected to both quickening and display aiding, then the human can perform an operation analogous to that of a simple relay.

In a recent report from Ohio State a comparison was made between a quickened system and one involving both quickening and display aiding (6). The system employed those conditions shown in Figs. 5 and 7. There were two other variables of interest: input frequency (single sinusoids of 2, 4, or 8 cpm) and display mode (a continuous visual display showing a fixed reference and a cursor which moved back and forth continually showing the instantaneous amplitude and direction of tracking error vs. a discrete, three-light display). In the case of the latter display the human tracker was instructed to keep the center light lit and that if the right- or the left-hand light was "on" it meant that he had generated an error "to the right" or "to the left," respectively. It is apparent that the discrete (three-light) display can indicate the direction of system error, but that the display can convey little information regarding the amplitude of error. However, the continuous display indicates both directional and amplitude characteristics of error. It was predicted therefore that if the system were quickened, performance with the discrete display would be inferior to that with the continuous display, since under that condition the human must relate movements of his control device to both direction and amplitude. However, with quickening plus display aiding it was predicted that performance on one display would not differ from that on the other since only the directional aspects of error need be considered by the human.

The results of the study are shown in Fig. 8. There it can be seen that the predictions were substantiated in that with a quickened system the RMS tracking error with the discrete display was inferior to that with the continuous display, especially at the higher input frequencies (4 and 8 cpm), while performance with the two displays did not differ when both quickening and display aiding were employed.

In summary, the transfer function techniques have provided psychologists with a most powerful tool for his research on human information-processing behavior. These techniques not only have clarified the hypotheses concerning these internal determinants of human behavior, but have opened up wide vistas to the psychologist for further quantification of human behavior. It should be of some satisfaction to those whose primary interests exist in the physical sciences to know that work in their field will have a significant and lasting effect on psychological interpretations of human performance in closed-loop control tasks. Had the transfer function technique been available to Plato, Aristotle, and Descartes, it is quite likely that we would understand today much more of man's internal determinants than is the case.

Engineers in the past have often conceived of new control systems by observing some of the more obvious and crude aspects of the human operator (7); today and in the future the engineer will be even more directly influenced in his design of new systems by the findings of the psychologists.

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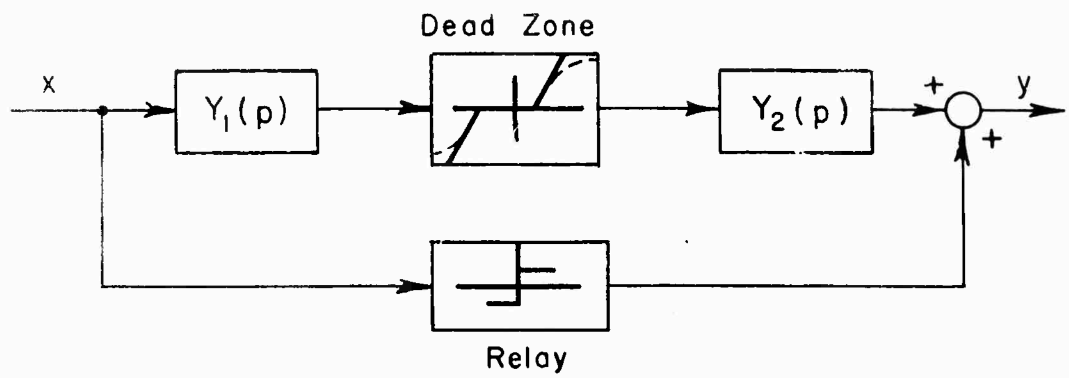

Fig. 1. Block diagram of Goodyear simulator of the human operator.

$$Y_1(p) = k_2p^2 + k_1p + k_o$$

$$Y_2(p) = e^{-\tau_o p}/(\tau_1 p + 1)$$

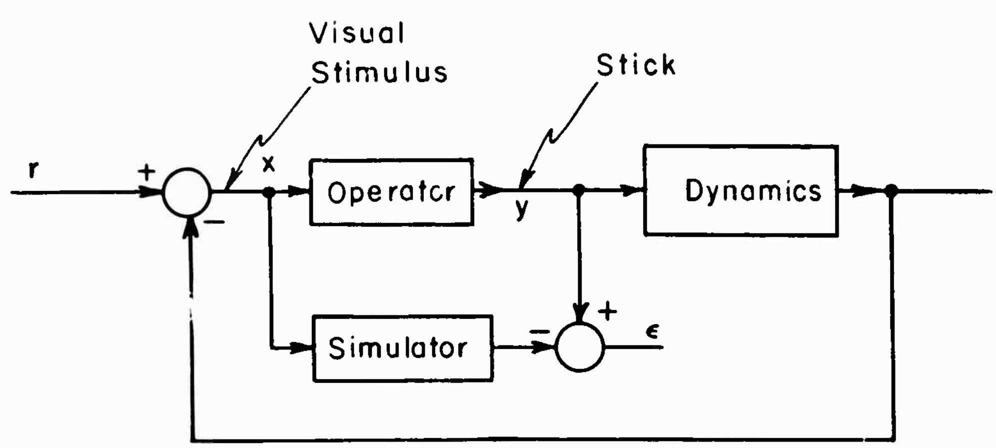

Fig. 2. Typical block diagram of system with operator in closed loop complex. Note simulator adjusted to minimize $\overline{\epsilon^2}$.

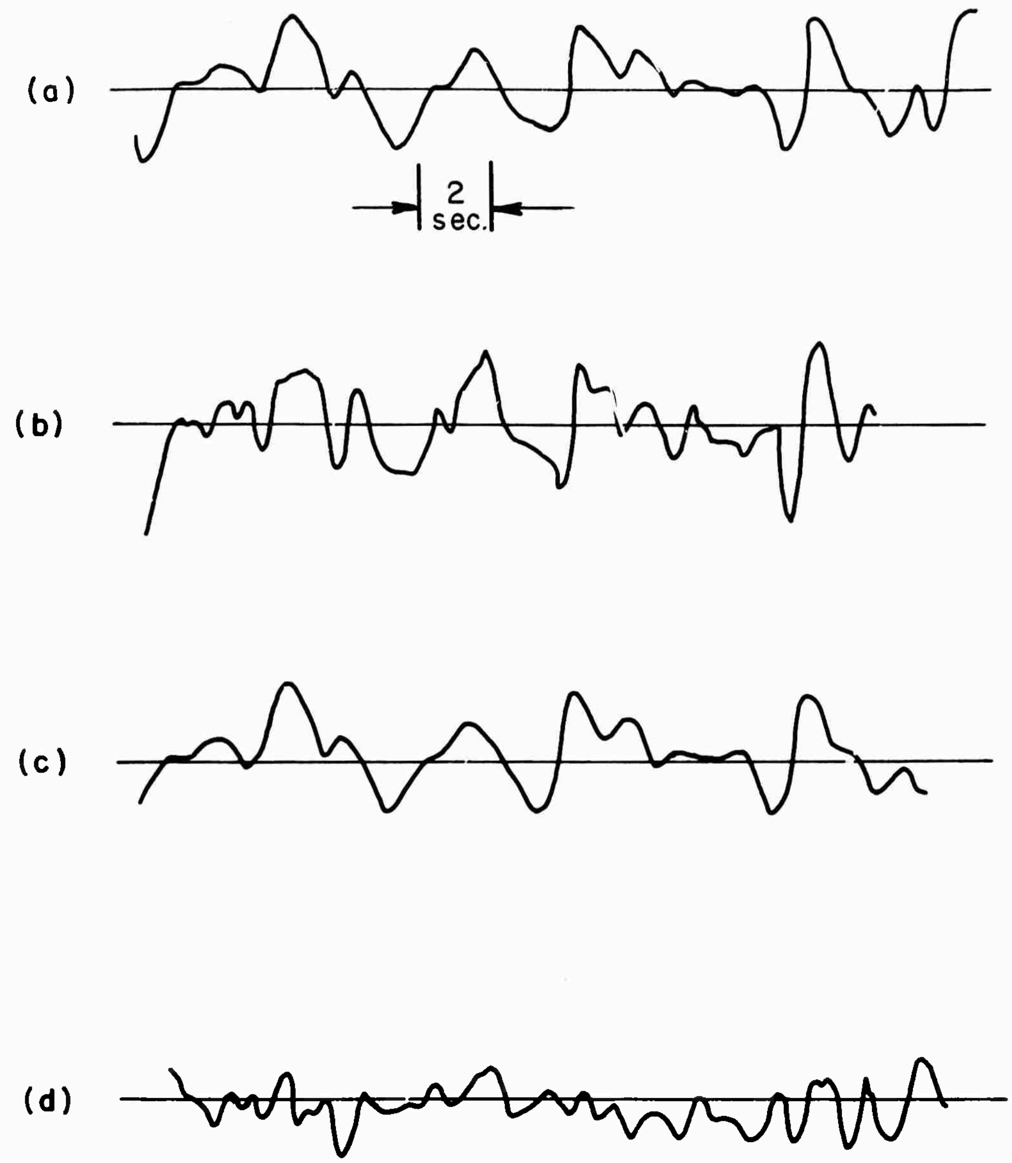

Fig. 3. Typical response of human operator.
(a) stimulus x
(b) operator response y
(c) G(p)x
(d) remanent y-G(p)x

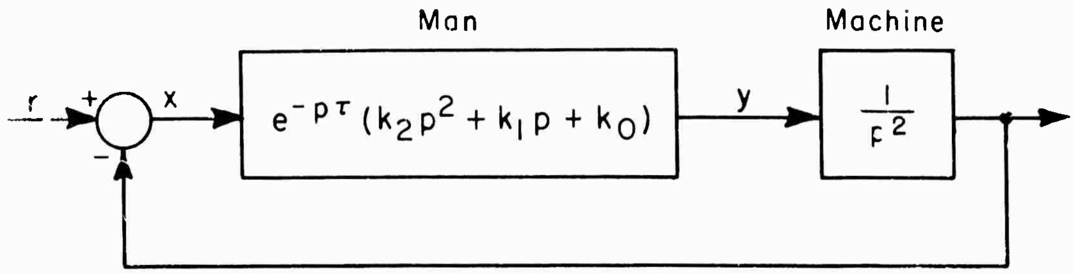

Fig. 4. Approximate linearized representation of operator in complex which forces operator to generate derivatives of x for stability.

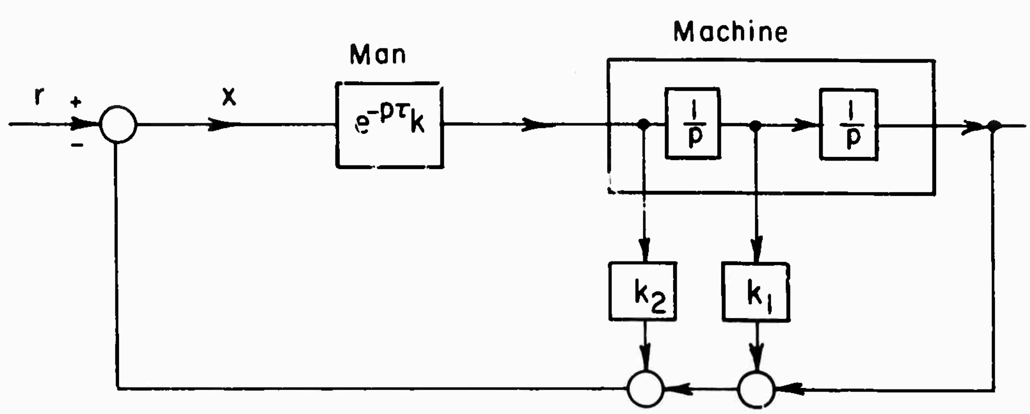

Fig. 5. Linearized representation of system shown in Fig. 4, with the operator properly matched to the system so as to improve response characteristics.

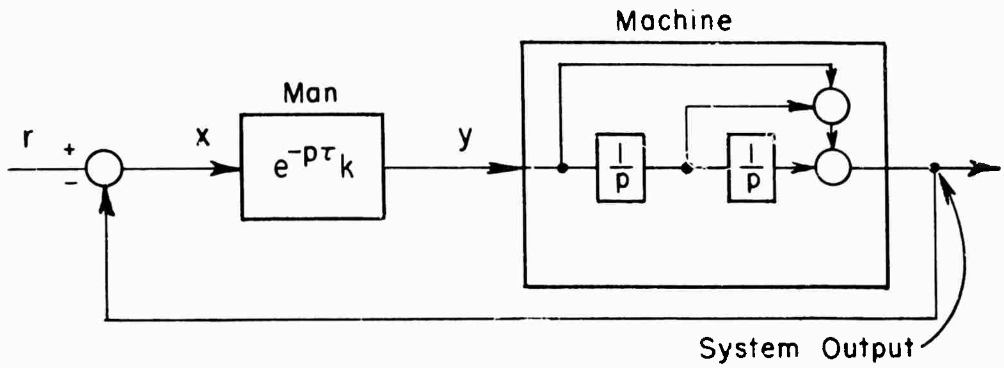

Fig. 6. The aiding operation applied to a man-machine system.

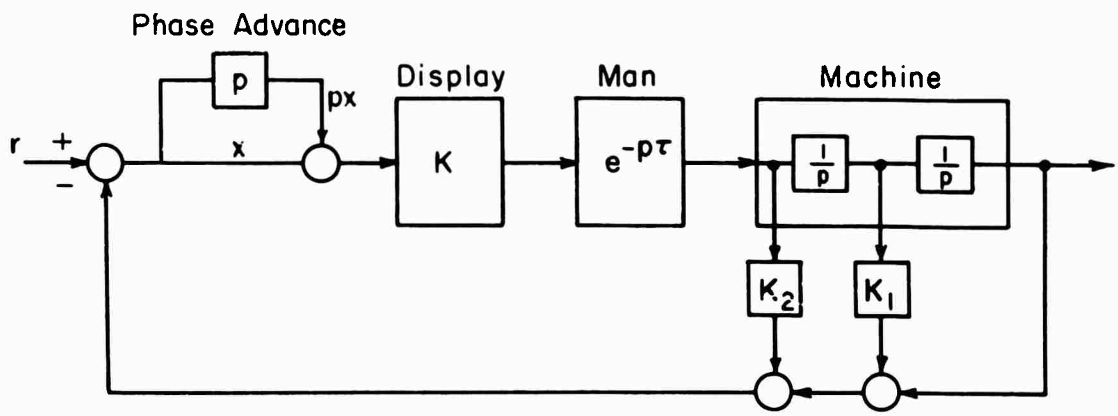

Fig. 7. Quickening and display aiding as applied to a Type II system.

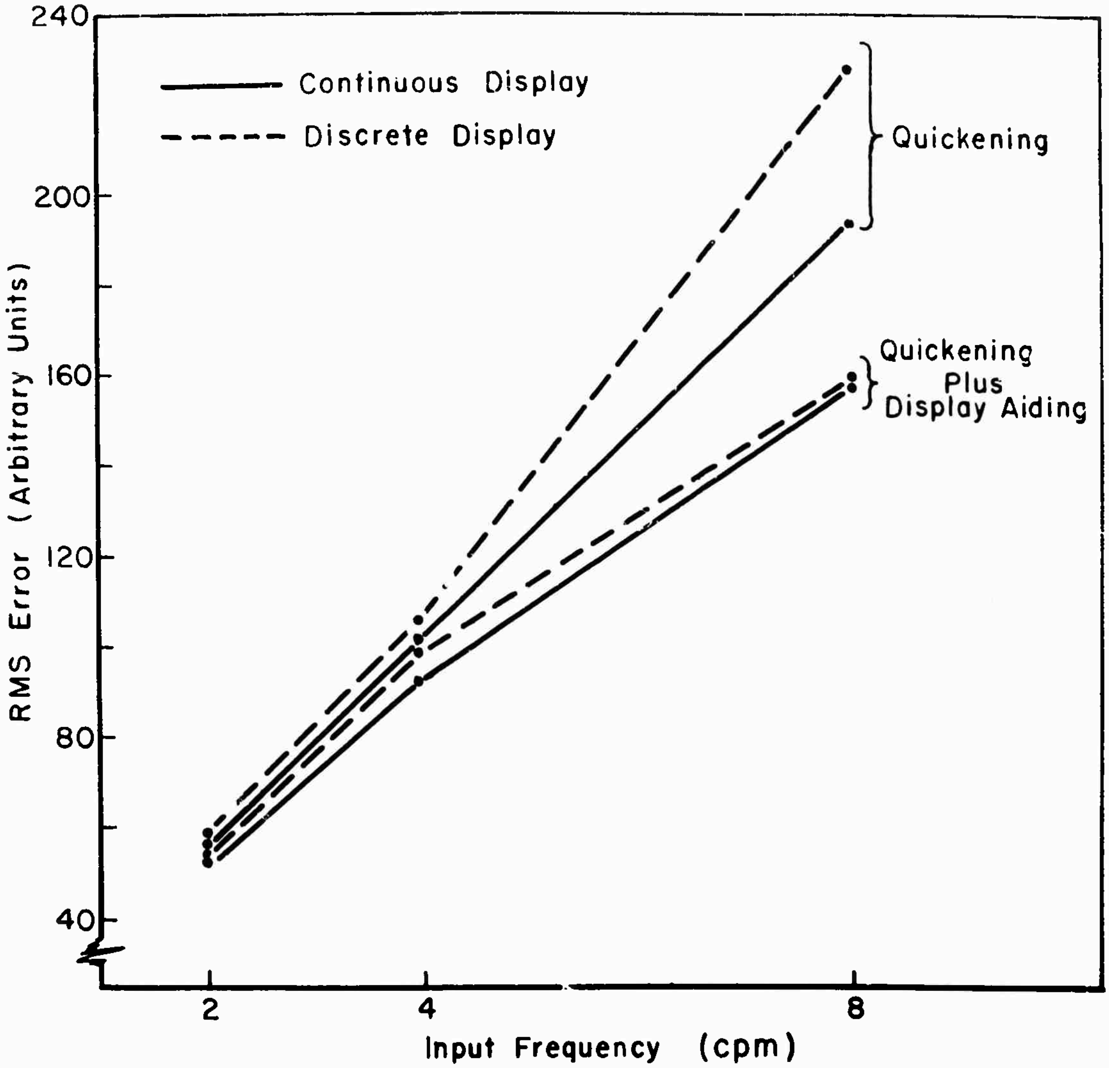

Fig. 8. Tracking accuracy in a Type II system as a function of display mode (discrete vs. continuous), input frequency, and quickening vs. quickening plus display aiding.

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